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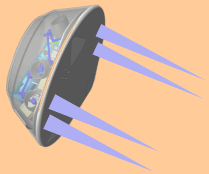

Supersonic Retropropulsion on Robotic Mars Landers: Selected Design Trades

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Outline

- **Supersonic Retropropulsion (SRP) introduction and background**
  - What is SRP and why do we care?
- **Legacy bank-control vs flapped vehicle architecture**
- **Monte Carlo study**
- **Notional vehicle configuration and sizing**
- **Conclusions**

Terms

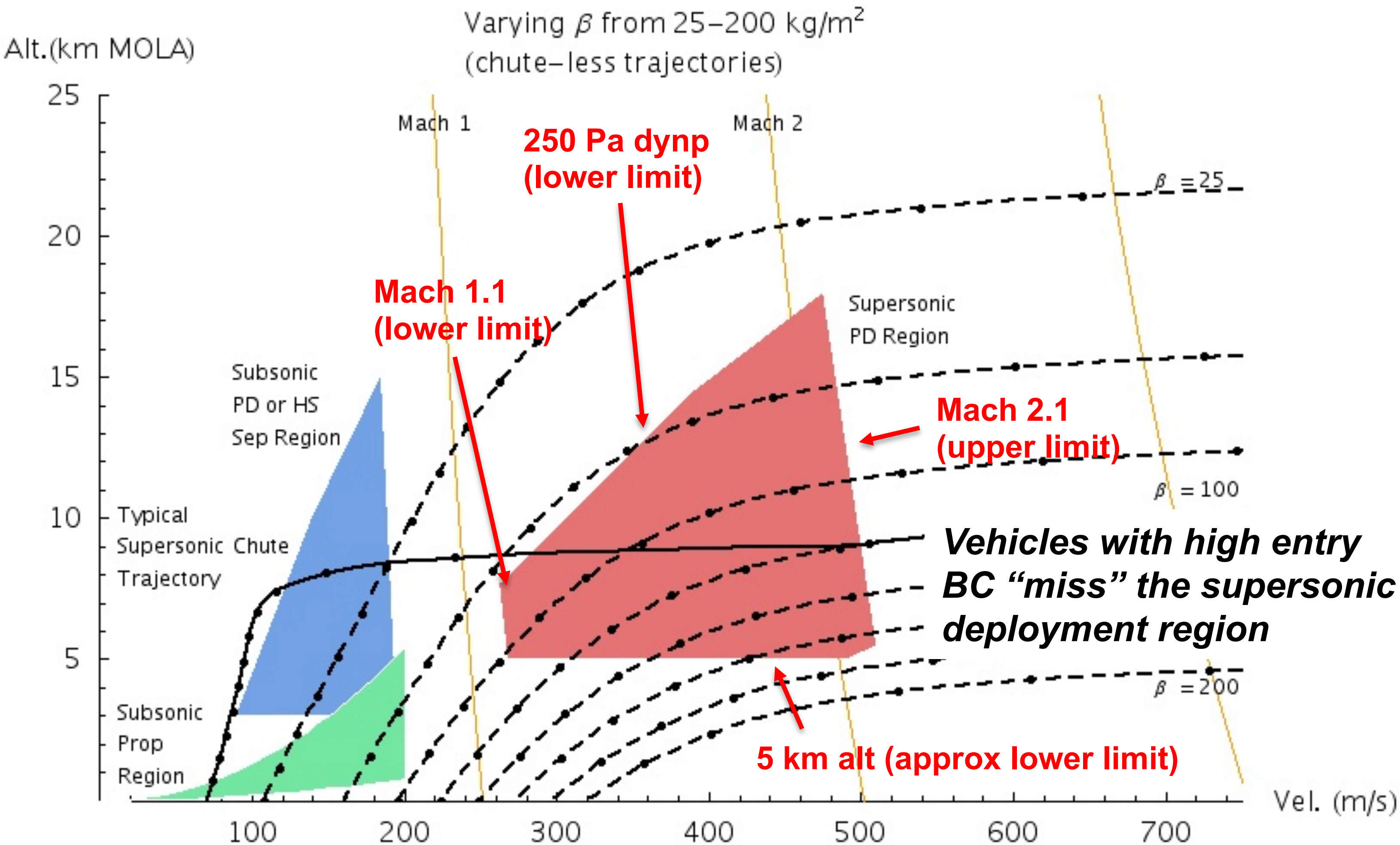
- **Ballistic coefficient: M / (Cd * A)**
  - M: entry mass
  - Cd: drag coeff
  - A: reference area (for entry vehicles, area of the heatshield)
  - Example #s:

	~ MSL		
Entry ballistic coeff (kg/m^2)	150	300	450
Entry mass w/4.7m aeroshell (kg)	3813	7627	11440

- **Propellant Mass Fraction (PMF): Mp / Mign**
  - Mp: propellant mass at ignition (not including RCS prop expended prior to ignition)
  - Mign = total wet mass at ignition

The "Viking Heritage" Ballistic Coefficient Limit

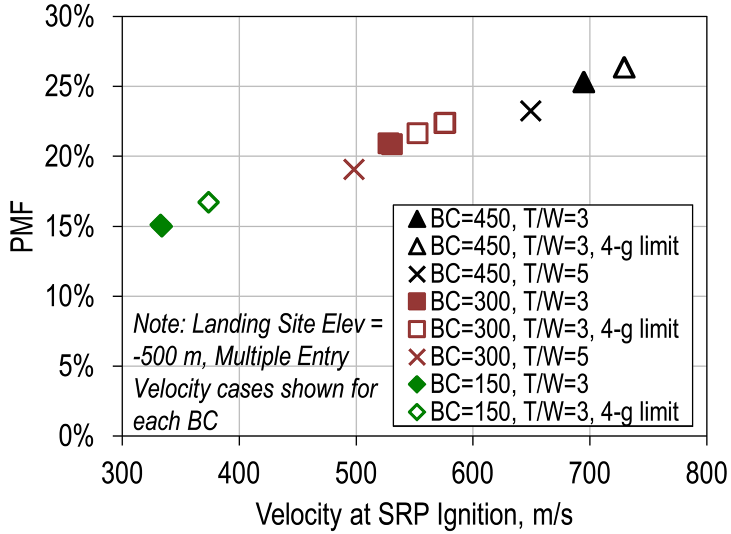
R.D Braun and R. M. Manning, "Mars Exploration Entry, Descent, and Landing Challenges." Journal of Spacecraft and Rockets. Vol. 44, No. 4, 2007, pp. 310-323.

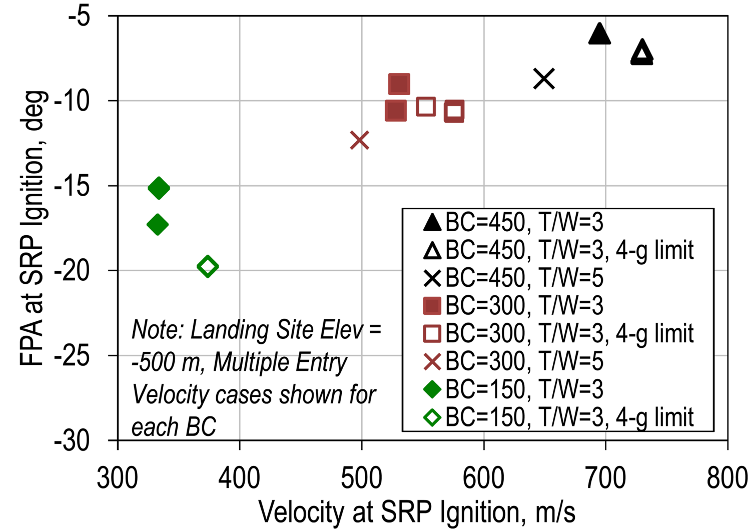


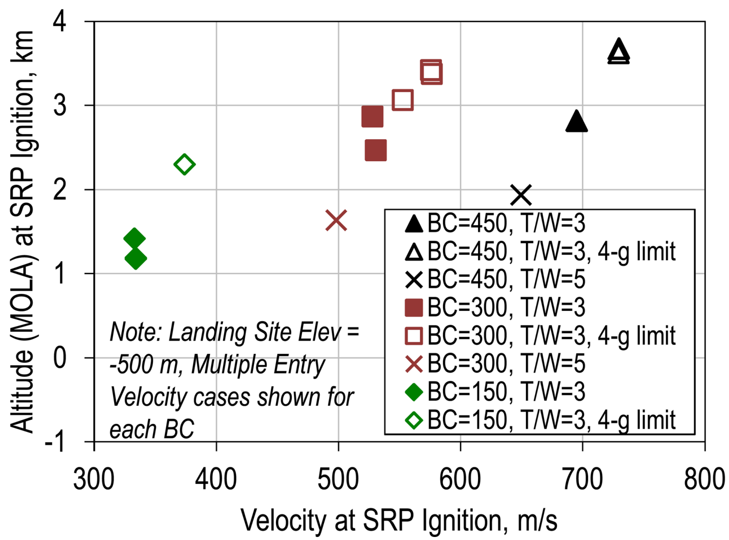
Vehicles with high entry BC "miss" the supersonic deployment region

Vehicles with High Entry BC Can Be Flown with SRP

Lobbia, M., Wolf, A., Whetsel, C., “Supersonic Retro-Propulsion for Future High-Mass Robotic Mars Lander Missions,” ISTS Conference 2017







PMF requirement varies with ignition speed

Optimal ignition speed varies with entry BC

Weaknesses of Legacy Bank-Control Architecture

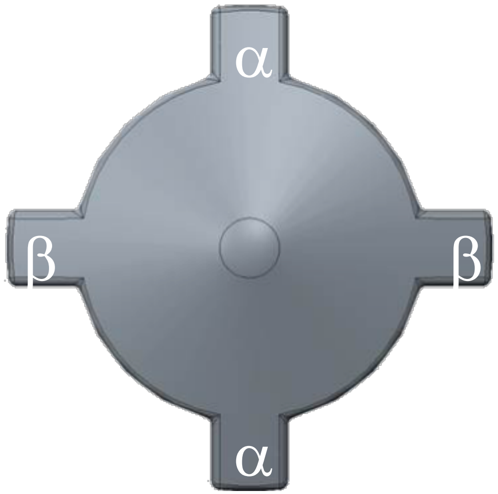
- **Offset center of mass is required during entry – but not during cruise**
  – Motivation for entry and cruise balance masses on Mars Science Laboratory (MSL), imposing mass penalties

- **Bank reversals are required to prevent excess lateral error, to stay within entry corridor**
- **Bank reversals instantly induce non-deterministic non-linear position errors, diminish overall control authority, and complicate the design and use of sensors during entry**
  – Control is essentially “off” for ~10-20% of the time during entry, during which range error grows significantly and can be reduced to pre-reversal levels only if there is enough time to go

Flapped Vehicle: A Proposed Alternative Approach

Korzun, A., Dutta, S., Dwyer Cianciolo, A., “Blunt Body EDL System Performance Improvements Through Direct Force Control and Deployable Tabs,” presentation at the 14th International Planetary Probe Workshop, 12-16 June, 2017, The Hague, Netherlands

- **Four articulated flaps equally spaced about the perimeter to modulate the center of pressure relative to the CG**
  - Roll rate and fixed roll attitude are maintained fixed using small RCS.
- **“Vertical” flaps modulate angle of attack**
  - Max AoA and L/D depends on flap size (Apollo and MSL: max L/D ~0.3)
- **“Lateral” flaps modulate side force to control sideslip / heading**
- **No bank reversals to degrade range error**
- Also possible to modulate drag: all 4 flaps move collectively to adjust for density variation so that velocity never deviates from the reference trajectory
  - *Not done in current simulation*
- **Mass needed for CG offset management and for bank-control thrusting is reduced, and could offset mass needed for flaps**



Flap Actuation for Lift and Side Force Control

- **Apollo entry guidance commands the vertical L/D component**
  - $Cl/Cd = (L/D)_{vertical}$
- **The lateral acceleration command is proportional to the heading error and current available lift:**
  - $A_{side} = K*L*\Delta\psi$
- **From A_{side}, an estimate of the desired side force coefficient can be obtained**
  - $Cy = A_{side}/qS$
- **A 2D search is performed in the aerodatabase (combined MSL + flap deflection "deltas") to find the vertical and horizontal tab deflections δv and δh that provide both Cl/Cd and Cy**

Monte Carlo Study

Objective: Comparison of the performance of bank-control and flapped vehicles (especially propellant requirement) in the presence of uncertainties

Selected assumptions

Parameter	Units	Value
Mars arrival Ls	deg	150
Inertial entry speed	km/s	6.5
Nominal Atm dusttau		0.48
Landing site elevation	m	-500
Targeted vert spd at ldg	m/s	0.75
Aeroshell diameter	m	4.7
Entry ballistic coefficient	kg/m^2	450
L/D at entry		0.24
Entry mass	kg	11440
Propellant Isp	sec	295
T/W at ignition		3

"worst" atmosphere, 2028 launch oppportunity

Biprop system

- **More assumptions**
  - Same entry state, entry guidance reference trajectory, atmosphere, and vehicle mass properties used for flapped & bank-control vehicles
  - Engine throttling constraint: 50% of maximum thrust
  - Flapped vehicle:
    - Each flap 6% of vehicle area, 20 deg. range of motion
    - Alpha flap limit 140 deg/s; Beta 33 deg/s (optimized for stability in alpha & beta – no design of actuators etc. to establish realistic limits)
  - Bank-control veh: bank rate limit 20 deg/sec, bank accel limit 5 deg/sec^2

Simulation Modeling

- **Entry Aerodynamics**
  - MSL LaRC 6-DOF aero with uncertainties
  - LaRC flap aerodatabase tables applied as deltas to MSL aero
- **Powered desc guidance algorithm: G-FOLD (Guidance for Fuel-Optimal Large Divert)**
- **No drag modeled after ignition**
  - High Mach: SRP pushes shock away from the vehicle => minimal drag
  - Subsonic speeds: drag uncertain, however not modeling drag is "conservative" because drag reduces propellant consumption

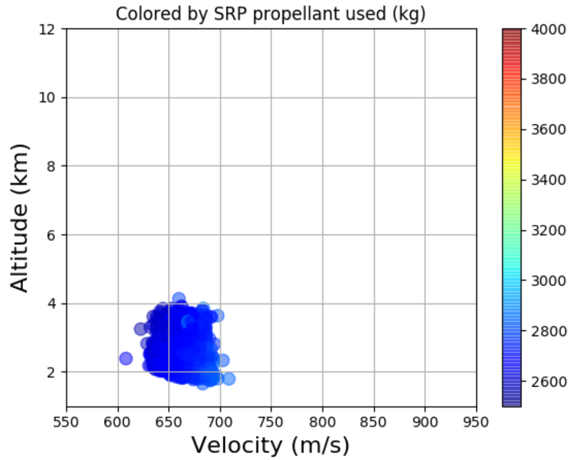
	ROLL-CONTROL VEHICLE	FLAP-EQUIPPED VEHICLE
Entry phase		
Guidance	Apollo entry guidance (generates bank angle commands)	Modified Apollo entry guidance (generates flap deflection commands)
Control	Bank angle changes to follow guidance commands, torque applied to s/c specified as function of commanded bank (no thruster firings modeled)	Flap deflections to follow guidance commands, with flap motion at hypothetical rate & acceleration.
Body dynamics / forces	Lift and drag vectors calculated from 6dof aerodatabase	Lift and drag vectors calculated from 6dof aerodatabase + "delta" aerodatabase for flaps
Knowledge sensing	no sensors modeled ("perfect knowledge")	no sensors modeled ("perfect knowledge")
Powered descent phase		
Guidance	G-FOLD generates required thrust magnitude and direction	G-FOLD generates required thrust magnitude and direction
Control	Exactly follows commands prescribed by powered descent guidance	Exactly follows commands prescribed by powered descent guidance
Body dynamics / forces	Thrust vector fixed in body coords, no aero lift or drag	Thrust vector fixed in body coords, no aero lift or drag
Knowledge sensing	no sensors modeled ("perfect knowledge")	no sensors modeled ("perfect knowledge")

Propellant-Optimal Ignition Triggering

- **Method used in simulation (too computationally intensive for onboard use):**
  - Starting at threshold speed of 850-900 m/s, at each point along the trajectory, GFOLD computes the optimal powered descent trajectory to target landing site
  - If estimated prop required increases instead of decreasing, above a specified delta fuel mass tolerance, then trigger ignition
- **Future onboard method: table lookup**
  - Generate a table relating propellant consumed for a variety of ignition conditions (target-relative position & velocity)
  - Matlab prototype demonstrated but not used in present Monte Carlo simulation

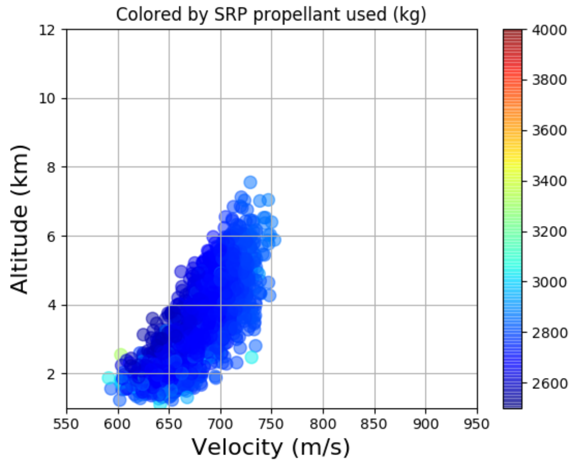
Monte Carlo Results: Velocity and Alt at Ignition

Flapped vehicle



	Ignition speed (m/s)	Ignition alt wrt MOLA (m)
Nominal	657	2684
mean	662	2624
std	12	491
99.87%	698	3881
0.13%	629	1754
Max	709	4125
Min	608	1652

Bank control vehicle

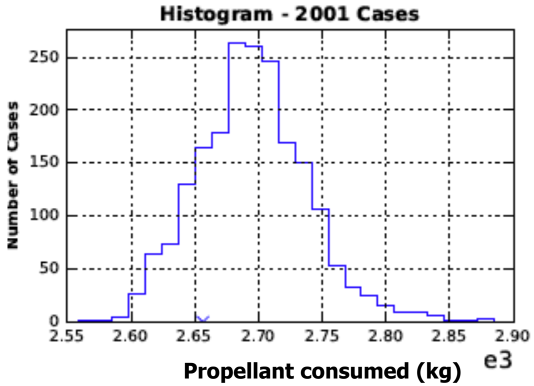


	Ignition speed (m/s)	Ignition alt wrt MOLA (m)
Nominal	654	2987
mean	677	2709
std	31	3307
99.87%	749	1241
0.13%	602	7038
Max	753	1233
Min	591	7549

Flaps reduce dispersions of speed and altitude at ignition compared to bank-control vehicle

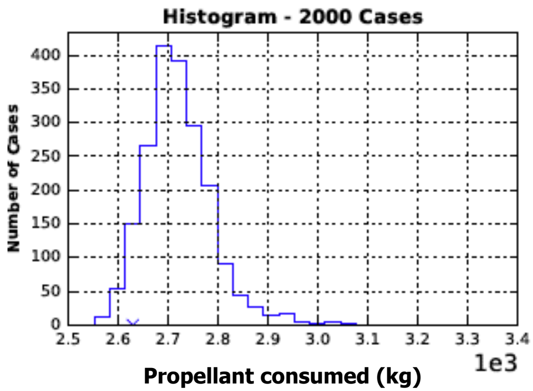
Monte Carlo Results: Propellant Consumption

Flapped vehicle



	Prop consumed, kg	PMF%
Nominal	2656	23.2%
mean	2695	23.6%
std	44	0.4%
99.87%	2878	25.1%
0.13%	2583	22.6%
Max	2885	25.2%
Min	2559	22.4%
99.87% - mean	183	1.6%
0.13% - mean	-112	1.7%

Bank control vehicle

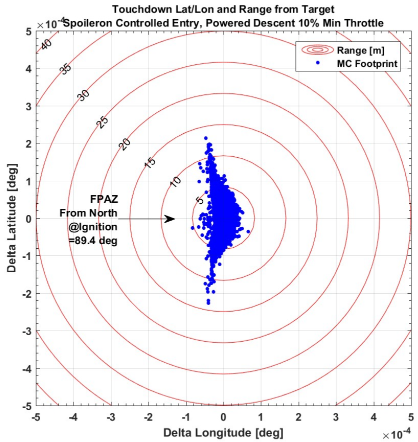


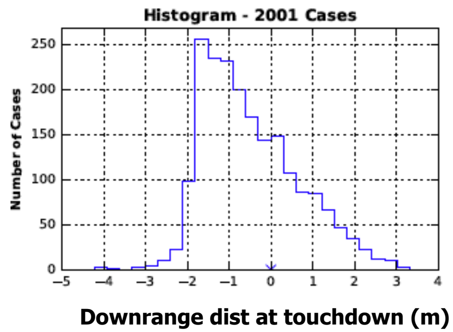
	Prop consumed, kg	PMF%
Nominal	2628	23.0%
mean	2719	23.8%
std	70	0.6%
99.87%	3082	26.9%
0.13%	2554	22.3%
Max	3321	29.0%
Min	2551	22.3%
99.87% - mean	362	3.2%
0.13% - mean	-165	5.3%

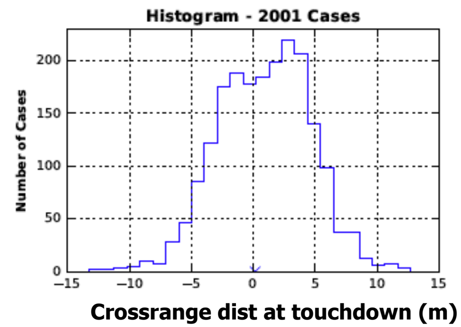
Flaps reduce propellant consumption dispersions by ~1% PMF

Monte Carlo Results: Landing Accuracy

Flapped vehicle

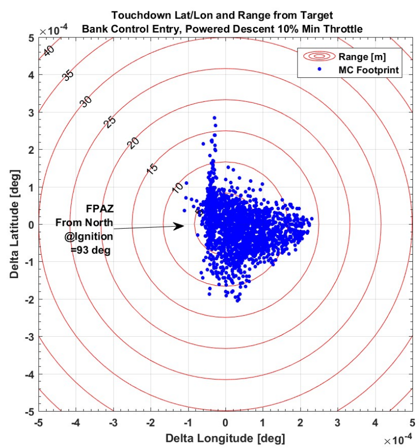


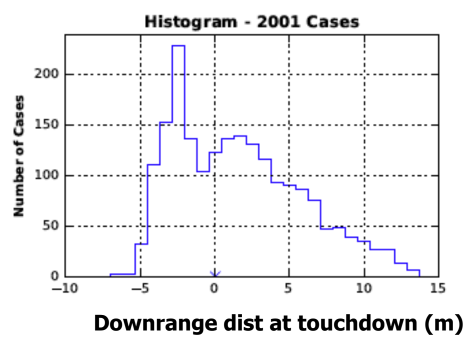


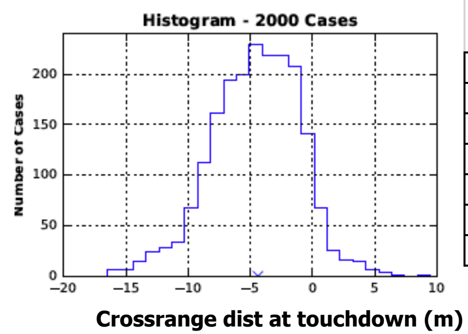


	Downrange dist at ldg (m)	Crossrange dist at ldg (m)
Nominal	0.00	0.00
mean	-0.49	0.91
std	1.14	3.71
99.87%	2.93	11.70
0.13%	-3.95	-11.47
Max	3.32	12.72
Min	-4.24	-13.32

Bank control vehicle





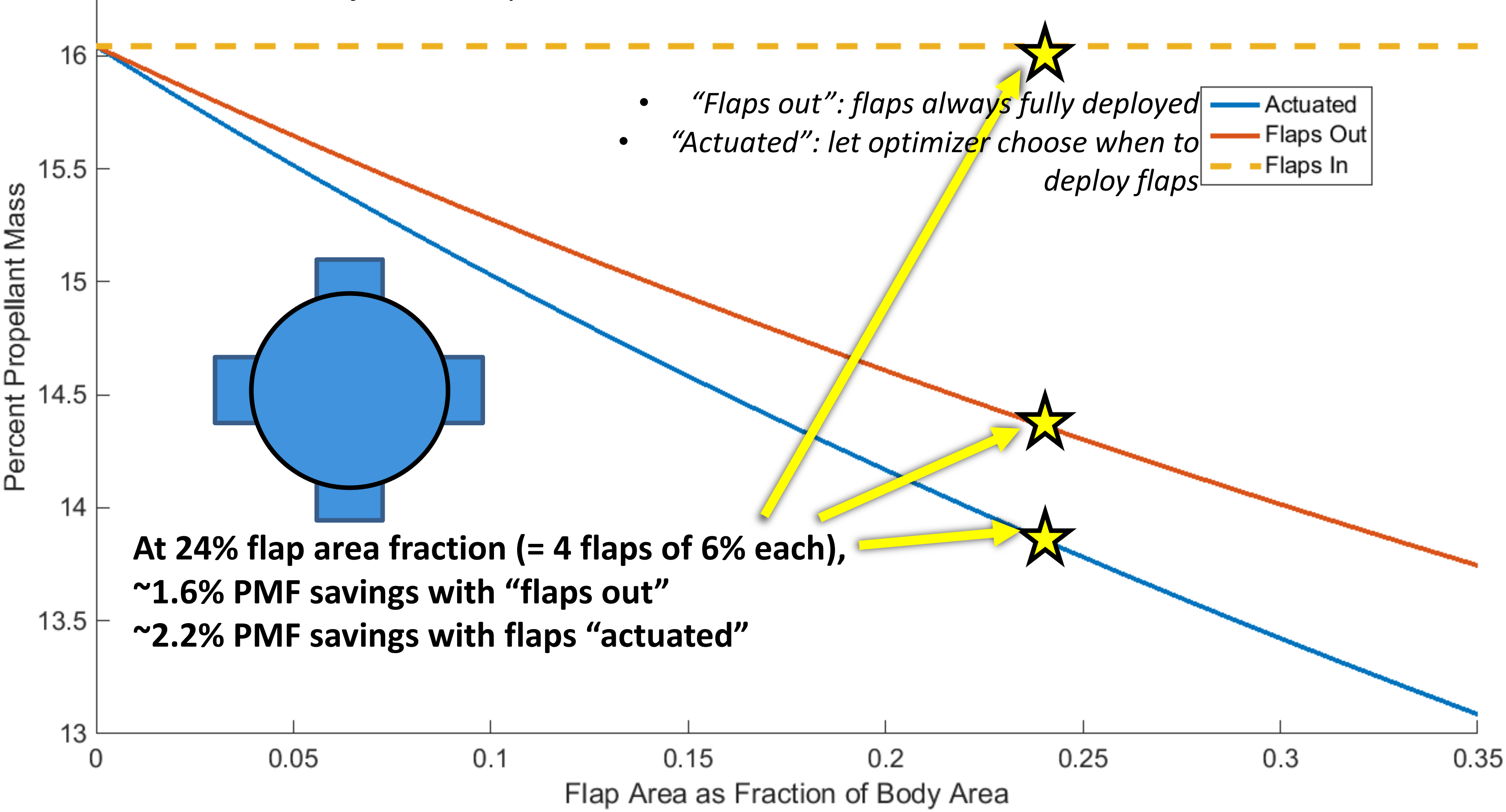


	Downrange dist at ldg (m)	Crossrange dist at ldg (m)
Nominal	0.00	0.00
mean	1.63	-4.56
std	4.27	3.57
99.87%	13.23	6.90
0.13%	-5.87	-15.96
Max	13.74	9.49
Min	-7.00	-16.52

All cases land within 20m of the target

Potential PMF Savings from Drag Modulation

- Effect of drag modulation emulated by:
  - *Modulating ballistic coeff as proxy for drag (increase area with const Cd)*
  - *Modulating lift by allowing L/D to vary*
- All trajectories optimized for minimum PMF

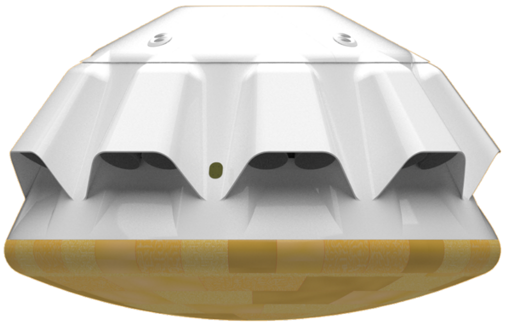


SRP Bank-Control Vehicle Concept

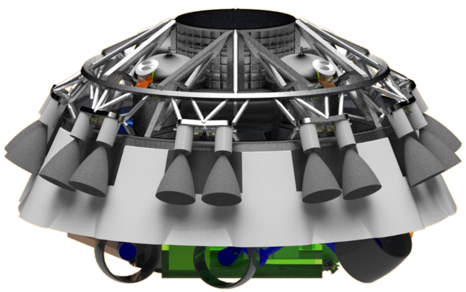
Baseline Configuration - Artist's Concept'

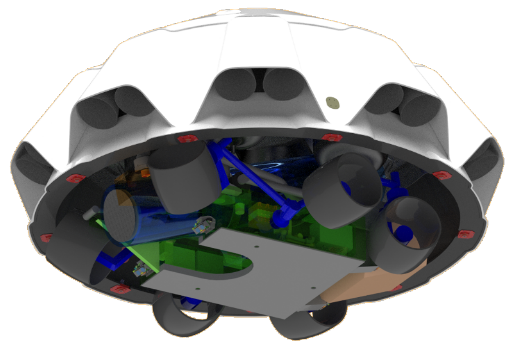
Heatshield jettisoned during powered descent when backshell thrust accel > heatshield drag accel (few hundred m altitude), to facilitate touchdown on wheels

Entry configuration



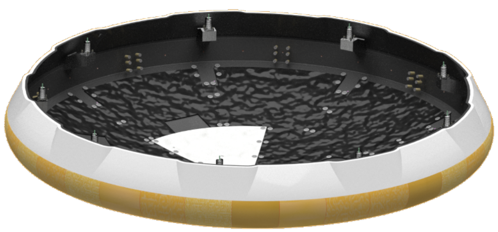
View of descent stage structure





Backshell is used as the ”skycrane” descent stage

Heatshield



Vehicle Sizing

- **Targeted 1300 kg landed payload mass**
- **Initial guess of entry BC = 250 kg/m^2 sized prop requirement and structural mass components**
  - PMF=22% + 3% for dispersions = 25%
  - Assuming 4.7 aeroshell, entry mass is 6355 kg (used for sizing of structural components)
- **Assumed 18 R-40 biprop engines for generous growth margin to maintain T/W ≥ 3**
  - Estimated 5460N max thrust with effective Isp of 250 sec (accounting for 30 deg engine cant angle and 0.985 plume loss factor)

Notional Mass Breakdown for Bank-Control SRP Sample Return Lander

	Mass estimate, kg (includes growth contingency)	Comments
Launch mass	**7860.33**	
Cruise Stage	789.00	structural mass scales with entry mass
Cruise Balance Mass	283.48	scales with entry mass
Entry mass	**6787.85**	
Entry Balance Mass	**318.13**	scales with entry mass
Wet mass at ignition	**6469.72**	
Avionics	75.84	
GN&C	39.03	
Telecom	36.80	
Thermal	34.35	
Harness	38.18	
Propulsion (dry mass)	734.85	
Mechanical	1264.80	scales with payload, portions estimated from CAD
Propellant	1617.43	25% PMF
Heatshield	1328.44	jettisoned at several hundred m alt prior to ldg
Payload	**1300.00**	

Entry ballistic coeff = 267 kg/m^2

18 R-40 engines provide T/W=3 for 7986 kg wet mass at ignition (~1400 kg greater than estimated 6470 kg wet mass at ignition)

Cruise and Entry Balance Mass Requirements

Need CM offset during entry, but don't want CM offset during cruise

Balance masses required?	**Chute-based architecture?**	**SRP bank-control vehicle?**	**SRP flapped vehicle?**
Cruise balance mass	Y	Y	N
Entry balance mass	Y	(?)	N

Needed to deploy chute at zero nominal angle of attack

May not be needed if vehicle can fly powered descent with an offset CM – future work

What About Launch?

Maximum launch masses for launch vehicles other than SLS in 2026 and 2028 opportunities (from NASA ELV Performance website)

	2026 opportunity	2028 opportunity
	C3=9.14 km^2/s^2	C3=8.93 km^2/s^2
Falcon Heavy (expendable), kg	10075	10130
Delta IV H (NLS II), kg	8600	9040
Atlas V 551, kg	5150	5170

At the modeled 7860 kg launch mass, possible to launch on Falcon Heavy or Deita IV-H in 2026 or 2028 with margin

Flapped Vehicle Mass Savings

	Launch mass savings	Entry mass savings	Comments
Prop mass savings from using flaps for AoA + sideslip control	64.69	64.69	1% PMF (1% of wet mass at ignition)
Potential additional prop mass savings from using flaps for drag modulation	129.38	129.38	max 2% PMF (2% of wet mass at ignition) - further analysis required to confirm
Eliminate cruise balance mass	283	0	
Eliminate entry balance mass	318	318	savings may be zero if balance mass can be eliminated from bank-control veh
TOTAL (flap system mass must be less than this for nonzero net mass savings)	**795.07**	**512.07**	

Need detailed estimate of flap system mass (flaps, TPS, actuators, other) to assess net savings

Conclusions

- **Significantly higher entry ballistic coefficients feasible with SRP enable heavier landed payload mass, even though prop mass requirement also increases significantly**
- **Preliminary SRP vehicle concept**
  - Lands 1300kg payload within capability of Delta IV-H or Falcon Heavy launch vehicle
  - Jettisons heatshield at several hundred meters above the surface
- **Recommended future work:**
  - Develop and test an entry guidance algorithm capable of both angle-of-attack modulation and drag modulation with flaps
  - Detailed mass estimation for flap system h/w including actuators
  - Investigate controllability during powered descent with offset center of mass

Backup

“Scaling” EDL (What is Scalable?)

- ***Scalable = invariant with S/C mass if the environment and GNC control methods / algorithms are kept constant***
- **Scalable entry phase parameters:**
  - Ballistic coeff
  - L/D
  - Bank profile constraints
  - Entry flight path angle

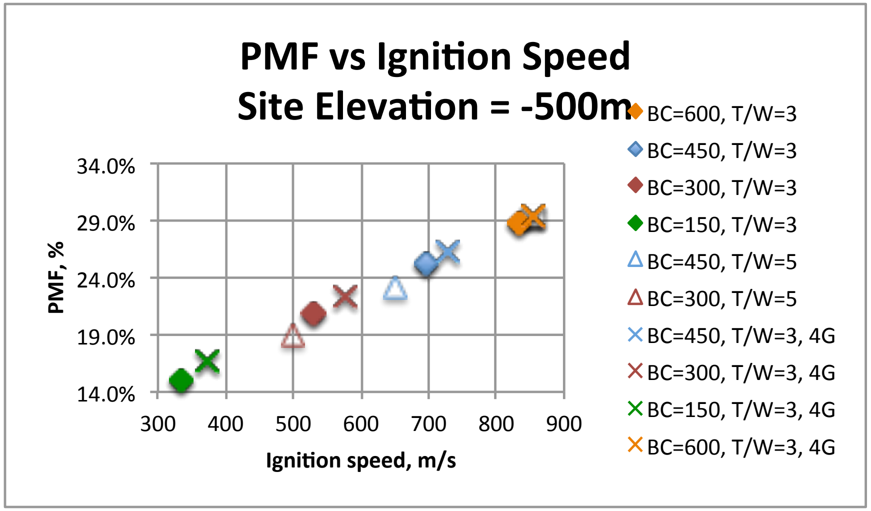
~ MSL

Entry ballistic coeff (kg/m^2)	150	300	450
Entry mass w/4.7m aeroshell	3813	7627	11440

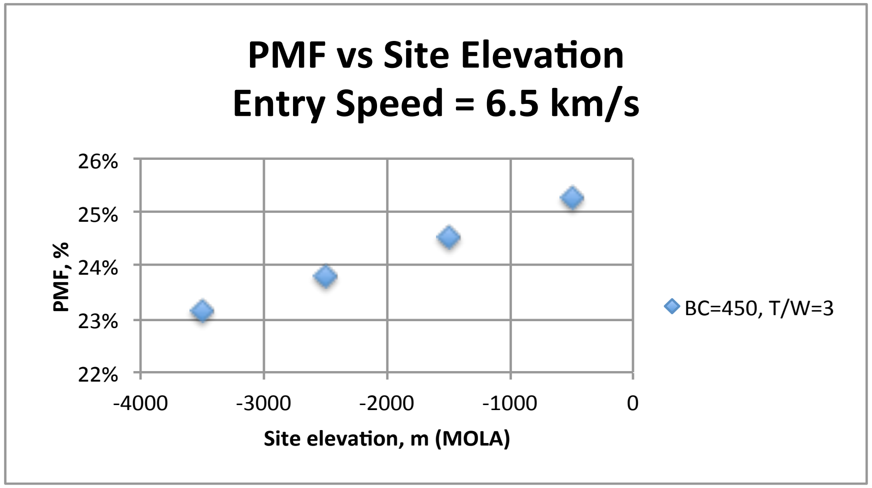
- **Transition from entry to powered descent: target-relative state (position and velocity vectors)**
- **Scalable powered descent parameters:**
  - T/W at ignition (note – weight calculated using Martian gravity)
  - Isp
  - **P**ropellant **M**ass **F**raction (**PMF** - propellant required / wet mass at ignition)
  - Engine throttling constraints (% thrust)
  - Targeted final conditions (V, ht above ground)

Ignition Conditions and Sensitivities

PMF = Propellant Mass Fraction (prop mass / wet mass at ignition)



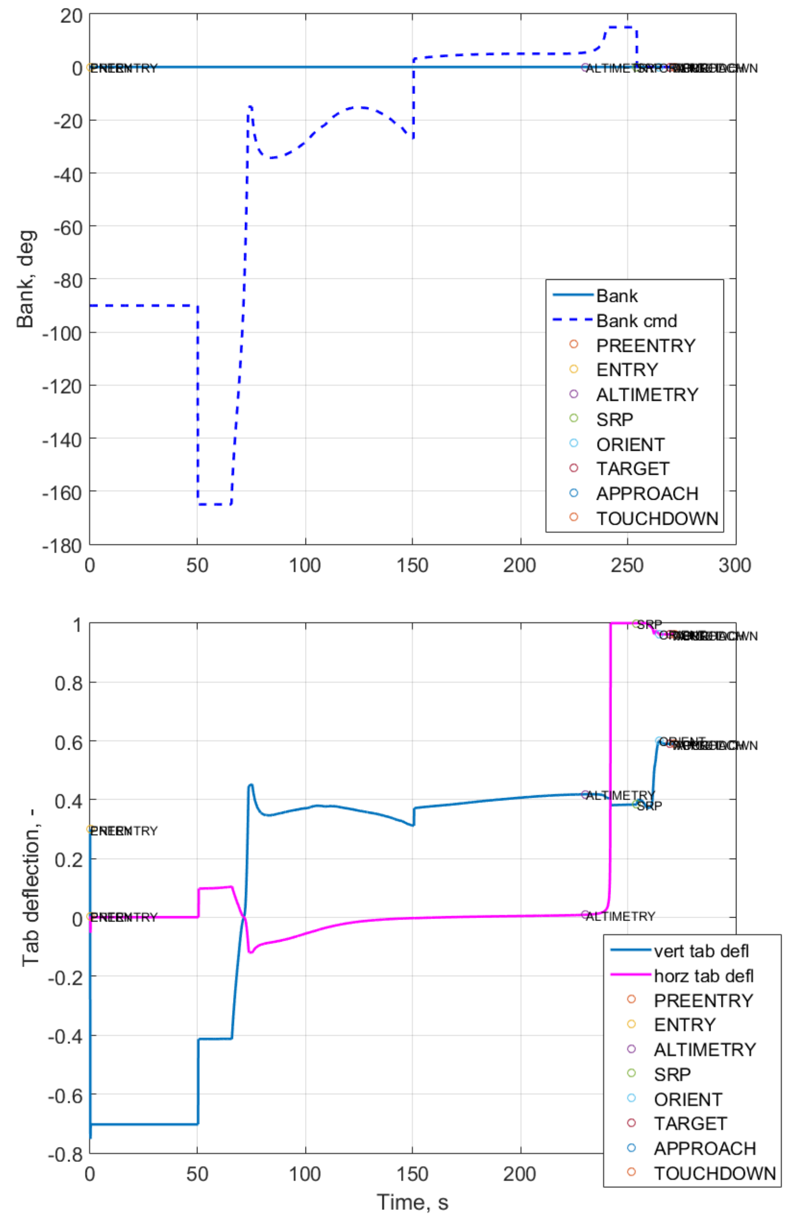
- *PMF sensitive to ignition speed (~3% per 100 m/s)*
- *Lower entry BC => slower ignition speed => lower PMF*
- *Increasing T/W from 3 to 5 produces modest (~2%) PMF savings*



- *Lowering site elevation reduces PMF by < 1% per km*

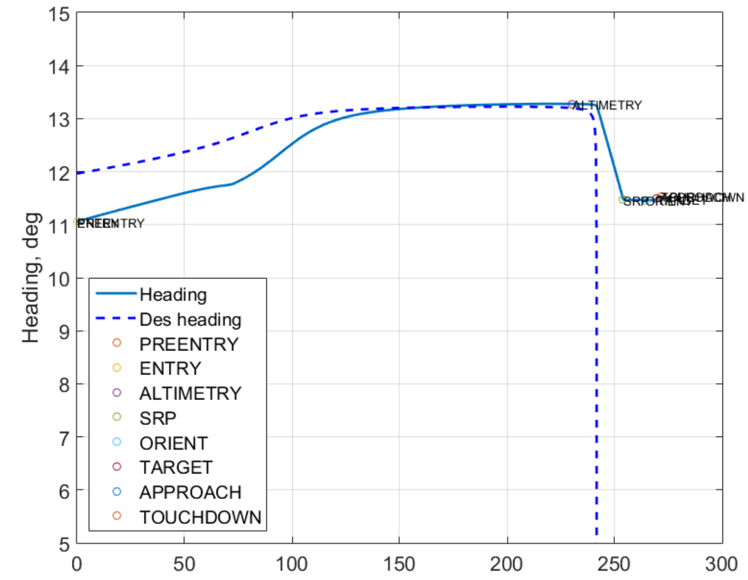
Flap Actuation for Lift and Side Force Control (1)

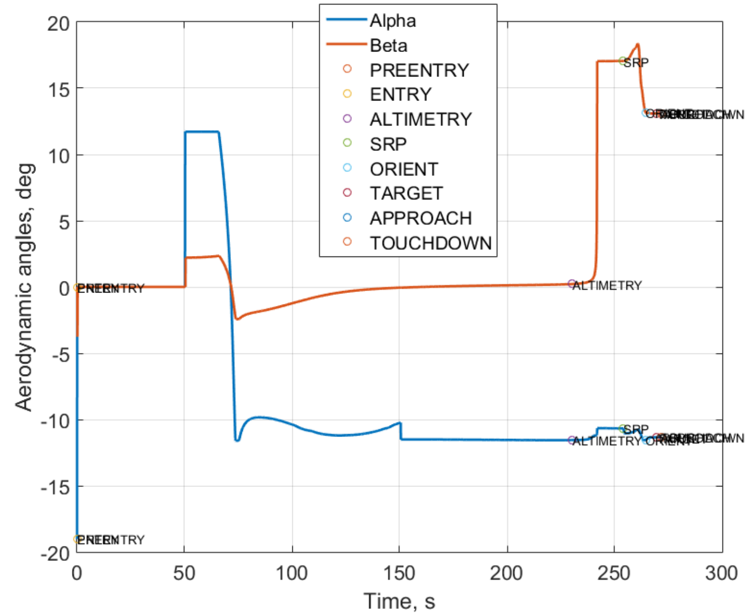
- **The Apollo bank command (dashed line in top-right plot) is used to obtain the desired vertical L/D**
  - $(L/D)_{vertical} = (L/D)_{available} * \cos(bank)$
- **From (L/D)vertical we can obtain the desired ratio of the desired lift and drag coefficients**
  - $Cl/Cd = (L/D)_{vertical}$
- **The lateral acceleration command is proportional to the heading error and current available lift:**
  - $A_{side} = K*L*\Delta\psi$
- **From A_{side}, an estimate of the desired side force coefficient can be obtained**
  - $Cy = A_{side}/pdyn/S$
- **A 2D search is performed in the MSL aero db + spoileron deflection delta database to find the vertical and horizontal tab deflections δv and δh that provide both Cl/Cd and Cy**



Flap Actuation for Lift and Side Force Control (2)

- Heading control brings the heading error to zero.
  - Dashed line in top-right plot is the desired heading (velocity vector pointing toward the target); solid line is the actual heading
- Additional accuracy can be achieved by adding a derivative term in the controller
- The resulting trim aerodynamic angles alpha (angle of attack) and beta (angle of sideslip) are shown in the plot in the bottom right

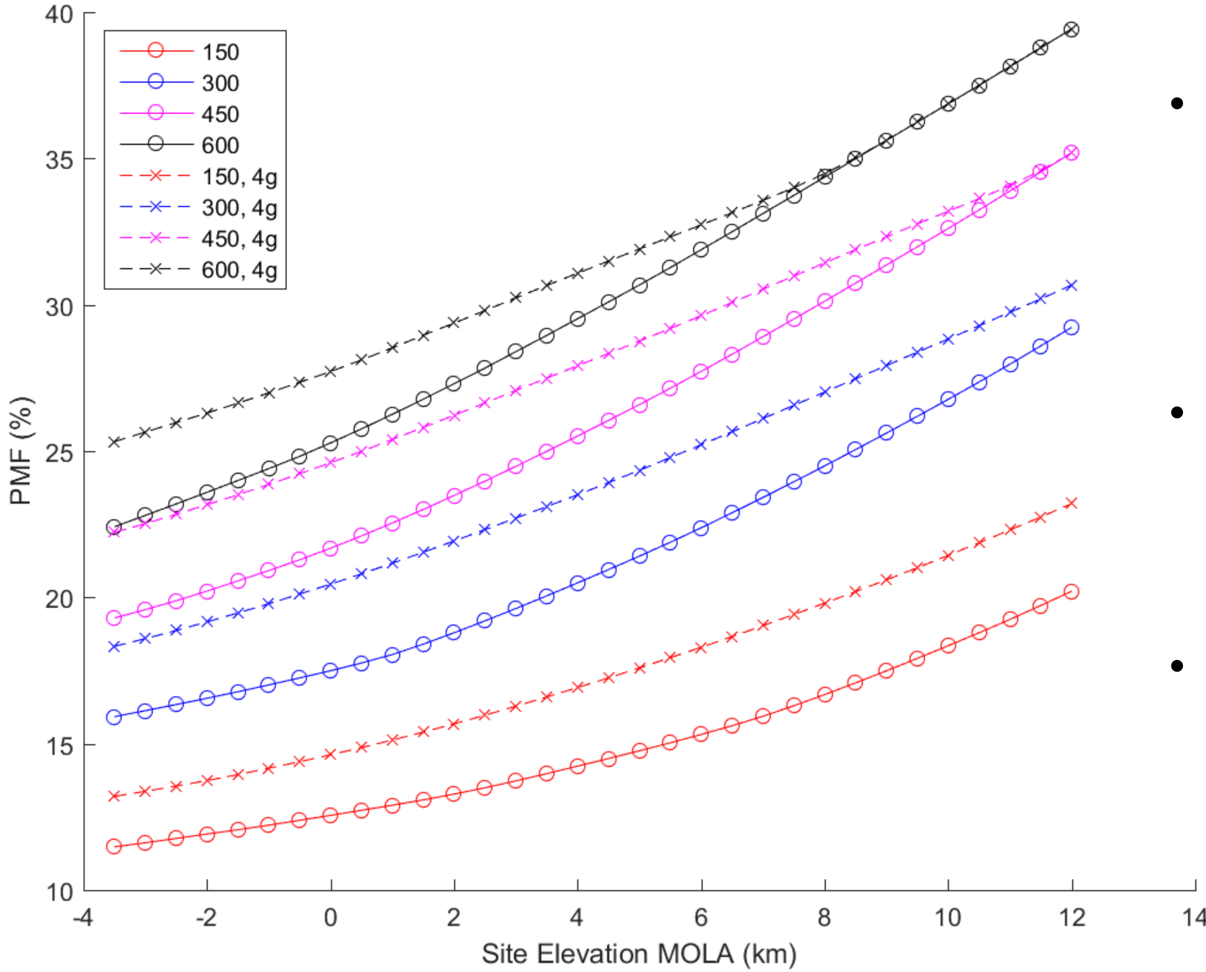




Control Inputs

- **Bank Control**
  - PD controller is used to apply Apollo commanded bank angle
- **Flap Control**
  - PID gains applied to both alpha and beta channels to reduce L/D and side slip errors
    - L/D gains are adjusted to match commanded vertical L/D profile
    - Side slip gains are adjusted to remove cross-track errors in nominal

Landing site elevation sensitivity study



- **At high landing elevations, the 4g load constraint is inactive and the two curves converge**
- **Penalty for imposing the load constraint is relatively small ~3% PMF**
- **Optimal SRP ignition altitude varies linearly with landing altitude**

R-40 Engines

- **Served as Shuttle RCS thrusters**
- **Biprop engine rated at 4000N thrust, Isp=281 sec with Shuttle nozzle configurations not optimized for thrust**
- **Custom version w/Shuttle injector and chamber and custom scarf nozzle (shaped for integration into our aeroshell) could deliver estimated 5460N max thrust at Isp=293 sec**
  – Effective Isp = 250 sec assuming 30 deg engine cant angle and 0.985 plume loss factor
- **Tested to 58% of max thrust on the ground, not throttled on orbit**
  – Development of throttle valve required for onboard throttling